Computer simulation of global profiles of carbon dioxide using a pulsed, 2-micron, coherent-detection, column-content DIAL system

Michael J. Kavaya, Upendra N. Singh, Grady J. Koch, and Jirong Yu

NASA Langley Research Center
Mail Code 468, Hampton, Virginia 23681 USA
michael.j.kavaya@nasa.gov

Rod G. Frehlich

University of Colorado
Cooperative Institute for Research in the Environmental Sciences (CIRES)
Campus Box 216, Boulder, Colorado 80309 USA

Abstract

We present preliminary results of computer simulations of the error in measuring carbon dioxide mixing ratio profiles from earth orbit. The simulated sensor is a pulsed, 2-micron, coherent-detection lidar alternately operating on at least two wavelengths. The simulated geometry is a nadir viewing lidar measuring the column content signal. Atmospheric absorption is modeled using FASCODE3P software with the HITRAN 2004 absorption line data base. Lidar shot accumulation is employed up to the horizontal resolution limit. Horizontal resolutions of 50, 100, and 200 km are shown. Assuming a 400 km spacecraft orbit, the horizontal resolutions correspond to measurement times of about 7, 14, and 28 s. We simulate laser pulse-pair repetition frequencies from 1 Hz to 100 kHz. The range of shot accumulation is 7 to 2.8 million pulse-pairs. The resultant error is shown as a function of horizontal resolution, laser pulse-pair repetition frequency, and laser pulse energy. The effect of different on and off pulse energies is explored. The results are compared to simulation results of others and to demonstrated 2-micron operating points at NASA Langley.

1 Motivation

The global measurement of atmospheric carbon dioxide dry mixing ratios has become very important for climate research, and it is one of 15 missions recommended to NASA by the National Research Council (NRC) in its recent Earth Science Decadal Survey (DS)[1]. It appears that laser remote sensing is the optimum technique for this application. Many types of laser remote sensing instruments have been proposed for the CO_2 space mission, and they have been compared in a recent study led by the French Institut Pierre Simon Laplace[2]. The French FACTS study, among others, has shown that the CO_2 absorption lines near 2 micron wavelength are very promising from a spectroscopic viewpoint. The 2-micron region is also attractive from a laser frequency control viewpoint[3].

NASA Langley Research Center (LaRC) has been developing 2-micron pulsed laser technology for about 20 years in order to enable a global measurement of wind from space[4], another NRC DS endorsed mission. At present, the baseline wind mission will employ both a direct-detection Doppler wind lidar at 0.355 microns, and a coherent-detection Doppler wind lidar at 2 microns. The coherent detection lidar will need a pulsed transmitter laser operating near 0.25 J

per pulse and 5 pulses per second. The laser development team at LaRC has been very successful and comprises pulse energy, efficiency, compactness, lifetime, conductive cooling, and beam quality efforts. Pulse energies of 1.2 J, which exceed the requirement of the first space winds mission, have been shown[5]. Ground-based wind measurements have been demonstrated with this technology[6]. The laser technology was used at LaRC to make a ground-based measurement of CO_2 that had very good precision[7].

With all the past effort on 2-micron pulsed lasers and coherent detection for a space winds mission, we decided to investigate the feasibility of performing the space-based CO_2 mission with coherent detection at 2 microns. One of the first steps was to develop a computer simulation of performance. We give preliminary results from the simulation here.

2 Computer Simulation

The simulation was programmed with Microsoft Excel. We began with column content measurements of CO_2 from earth orbit. The assumed parameters are listed in Table 1 below.

Table 1. Parameters for the Simulation

Molecule Measured	CO_2	
Measurement Technique	DIAL	
Vertical Resolution	Column	
Detection Technique	Coherent	
Laser Mode	Pulsed	
Orbit Height	400	km
Beam Direction	Nadir	
Telescope Diameter	0.5	m
Lambda High (On)	4875.648888 2.051009051	cm^{-1} microns
Lambda Low (Off)	4873.75 2.051808156	cm^{-1} microns
Earth Surface Reflectivity[3]	0.09	sr^{-1}

The expression for the error in measuring optical depth (OD) with coherent detection in the pulsed, column mode was provided by Frehlich[8]. We report here the results of the spectral method of estimating lidar return energies. We assume 20 spectral bins contain the entire signal and are used for the estimation. Parameters of the simulation are:

- Laser pulse energy
- Laser pulse-pair repetition frequency (PPRF)
- Measurement time = Horizontal resolution / Satellite velocity scaled to the earth surface

The number of laser shots comprising one measurement is the measurement time times the PRF. The four vertical profiles of atmospheric linear extinction coefficient and transmission from space were generated using PcLnWin/FASCODE3P software accessing the HITRAN 2004 absorption line data base[9].

3 Simulation Results

Figure 1 presents the simulation results for various combinations of laser pulse energy and PPRF. (If one laser is used with wavelength switching, the nominal laser PRF must be twice the PPRF.) The vertical axis is the error standard deviation of estimating OD. The horizontal resolution was 50 km giving a measurement time of about 7 seconds. The

measurement requirements listed in the NRC DS[1] were error of 0.005 (0.5%) and horizontal resolution of 100 and 200 km. The FACTS study[2] listed the requirements as 50 km horizontal resolution and error of 0.01 and 0.0025. (Error requirements refer to carbon dioxide dry mixing ratio. The error in OD is one part of that error budget.) Focusing on 50 km and 1% error, the figure shows that 0.1 mJ pulsed must be 20 kHz or more, 0.5 mJ pulses must be 2 kHz or more, and 1 mJ pulses must be 1 kHz or more.

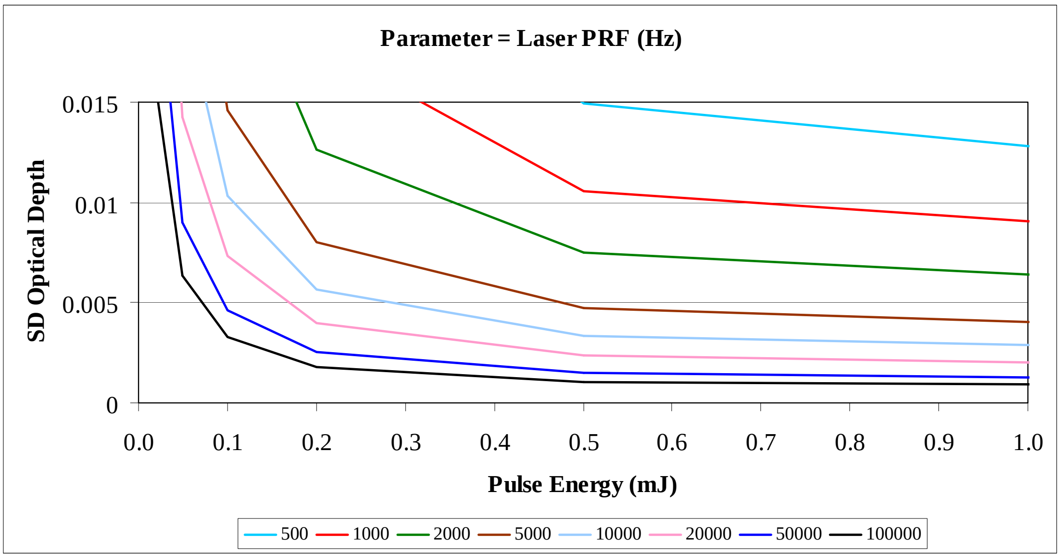

Figure 1. Results of simulation giving OD error vs. energy and PRF for 50 km horizontal resolution, 400 km, and 0.5 m

4 Comparison to Results in FACTS

To check if our simulation results are reasonable, we compared its results to some results in the FACTS study[2]. They assumed a 450 km orbit, a 1-m diameter telescope, a 10 kHz PPRF laser, and a required error of 1%. They permitted different pulse energies for the high (on) and low (off) wavelengths. The found a requirement for 0.045 and 0.015 mJ, respectively. Our results for this case are given in Figure 2.

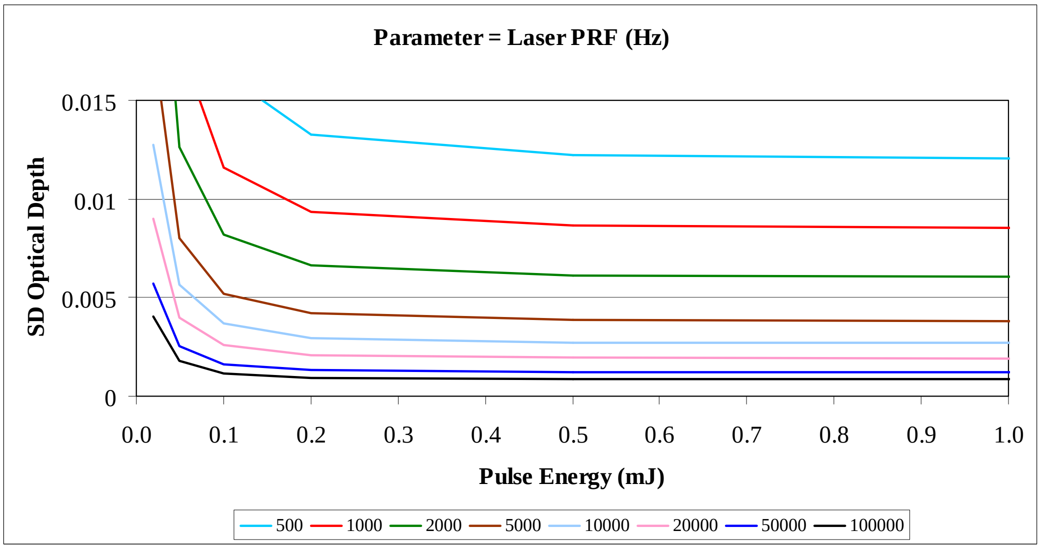

Figure 2. Results of simulation giving OD error vs. energy and PRF for 50 km horizontal resolution, 450 km, and 1 m

The light blue line corresponds to 10 kHz PPRF. An error of 1% is found for a pulse energy of 0.028 mJ. Doubling this for the total of high and low gives 0.056 mJ, which is very close to 0.06 mJ found in FACTS. As a better comparison we let the high and low pulse energies vary while holding the sum at 0.06 mJ. This produced Figure 3.

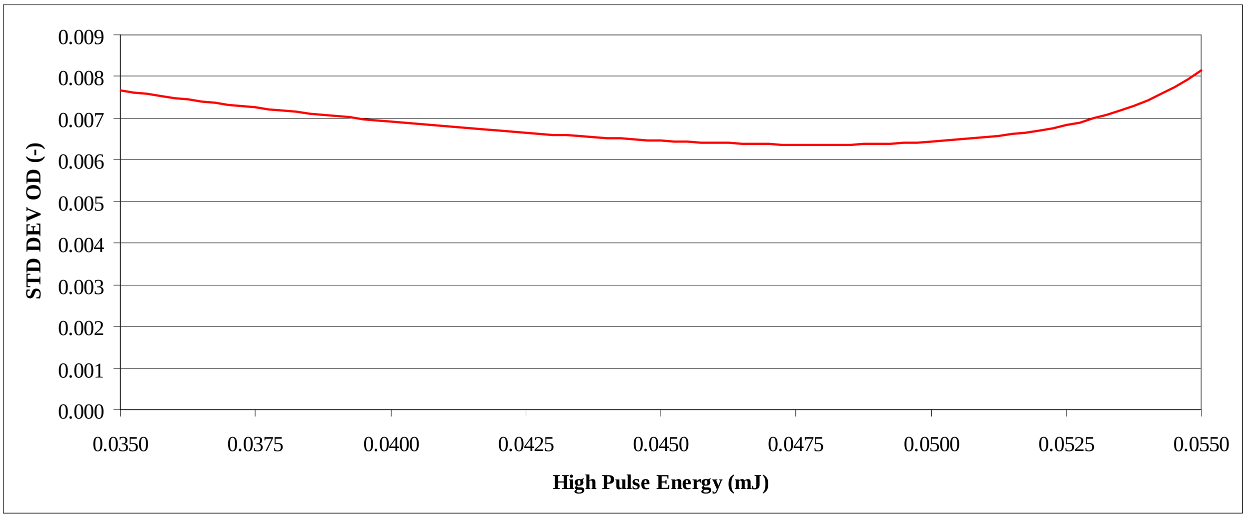

Figure 3. Results of simulation giving OD error vs. high pulse energy for 10 kHz, 50 km horizontal resolution, 450 km, and 1 m

The lowest error in OD occurs for high pulse energy of 0.048 mJ and low pulse energy of 0.015 mJ.

5 References

1. National Research Council (NRC), "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," The National Academies Press, Wash DC, (Jan. 2007), "Decadal Survey"
2. C. Loth, P. H. Flamant, F.-M. Bréon, D. Bruneau, P. Desmet, T. Pain, A. Dabas, P. Prunet, and J.-P. Cariou, "FACTS. Future Atmospheric Carbon Dioxide Testing from Space," Institut Pierre Simon Laplace et al, ESTEC Contract No. 17852/04/NL/CB (Nov. 2005)
3. G. Ehret, C. Kiemle, M. Wirth, A. Amediek, A. Fiz, and S. Houweling, "Space-borne remote sensing of CO_2, CH_4, and N_2O by integrated path differential absorption lidar: a sensitivity analysis," Appl. Phys. B 90, 593-608 (2008)
4. M. J. Kavaya, J. Yu, G. J. Koch, F. Amzajerdian, U. N. Singh, and G. D. Emmitt, "Requirements and Technology Advances for Global Wind Measurement with a Coherent Lidar: A Shrinking Gap," SPIE International Symposium on Optics & Photonics, Lidar Remote Sensing for Environmental Monitoring VIII, San Diego, CA (26-30 August 2007)
5. 3. J. Yu, B. C. Trieu, E. A. Modlin, U. N. Singh, M. J. Kavaya, S. Chen, Y. Bai, P. J. Petzar, and M. Petros, "1 J/pulse Q-switched 2-micron solid-state laser," Opt. Letters 31, 462 (2006)
6. G. J. Koch, J. Y. Beyon, B. W. Barnes, M. Petros, J. Yu, F. Amzajerdian, M. J. Kavaya, and U. N. Singh, "High-Energy 2-micron Doppler Lidar for Wind Measurements," Opt. Engr. 46(11), 116201-1 to 116201-14 (2007)
7. G. J. Koch, B. W. Barnes, M. Petros, J. Y. Beyon, F. Amzajerdian, J. Yu, Davis, S. Ismail, S. Vay, M.J. Kavaya, and U.N. Singh, "Coherent Differential Absorption Lidar Measurements of CO_2," Applied Optics 43(26), 5092-5099 (2004)
8. R. G. Frehlich, "Coherent Doppler Lidar DIAL Error Analysis," unpublished, U. of Colorado (2009)
9. Ontar Corp., Andover, MA USA, http://www.ontar.com/